

THERMOGRAPHIC ANALYSIS OF COMPOSITE COBONDS ON THE X-33

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ABSTRACT

During the manufacture of the X-33 liquid hydrogen (LH₂) Tank 2, a total of thirty-six reinforcing caps were inspected thermographically. The cured reinforcing sheets of graphite/epoxy were bonded to the tank using a wet cobond process with vacuum bagging and low temperature curing. A foam filler material wedge separated the reinforcing caps from the outer skin of the tank. Manufacturing difficulties caused by a combination of the size of the reinforcing caps and their complex geometry lead to a potential for trapping air in the bond line. An inspection process was desired to ensure that the bond line was free of voids before it had cured so that measures could be taken to rub out the entrapped air or remove the cap and perform additional surface matching.

Infrared thermography was used to perform the precure "wet bond" inspection as well as to document the final "cured" condition of the caps. The thermal map of the bond line was acquired by heating the cap with either a flash lamp or a set of high intensity quartz lamps and then viewing it during cool down. The inspections were performed through the vacuum bag and voids were characterized by localized hot spots. In order to ensure that the cap had bonded to the tank properly, a post cure "flash heating" thermographic investigation was performed with the vacuum bag removed. Any regions that had opened up after the preliminary inspection or that were hidden during the bagging operation were marked and filled by drilling small holes in the cap and injecting resin. This process was repeated until all critical sized voids were filled.

INTRODUCTION

The X-33 reusable launch vehicle technology demonstrator was designed to store liquid hydrogen fuel in a pair of composite fuel tanks, shown in Figure 1. Each multi-lobed tank is an integral part of the vehicle's load bearing primary structure. The tanks are attached to the rest of the airframe at points around their forward and aft ends. Adjacent to each of these attachment points, a cast structural foam filler and bonded reinforcing cap are used to distribute loads to the tank skins. The general locations of these caps are shown in Figure 2, viewing one of the tanks from the aft perspective. The typical cap geometry is evident from the photographs of bonded caps shown in Figure 3.

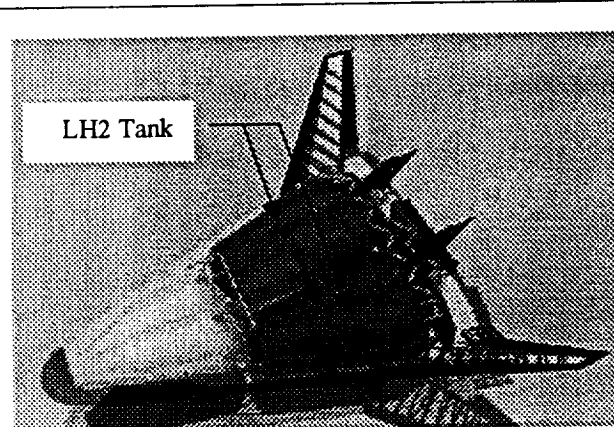


Figure 1. X-33 internal structure.

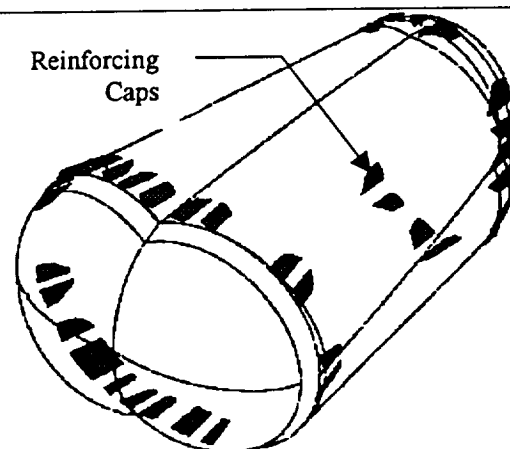


Figure 2. Locations of reinforcing caps on tank.

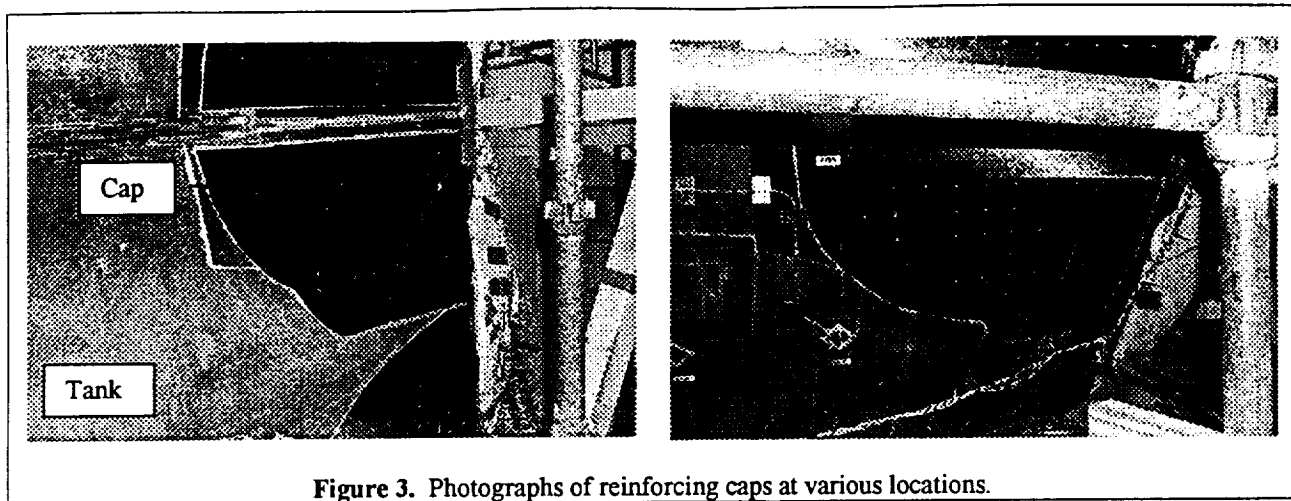


Figure 3. Photographs of reinforcing caps at various locations.

The method of thermographic inspection employed to inspect the bond lines consists of exposing the reinforcing cap surface to a rapid heat flux by pulsing a pair of high intensity flash lamps or slowly saturating the surface with heat using lower intensity hand-held quartz lamps. After the cap has been heated, an infrared camera is used to record the surface temperature as the heat transfers into the structure and the cap begins to cool. A void between the cap and underlying foam acts as an insulator, and that region of the cap will retain higher temperatures over the void than the surrounding area. Bond line voids are thus indicated as bright "hot" regions in the thermographic images.

Thermographic inspections of the wet bond line prior to curing required a novel bagging method. The thermographic imager was capable of viewing the temperature of the cap surface through the bagging and release ply material, but could not image through a traditional breather cloth, used to ensure thorough evacuation of the vacuum bag. It was also determined that when air was trapped in the bond line it was very difficult to get it to move to the edge of the cap so that it could be evacuated. The solution to this problem involved drilling a grid of vent holes over the acreage of the cap and placing a series of split, cut in half along their length, plastic tubes over the cap vent holes to facilitate evacuation. This arrangement required that minimal breather cloth only be used around the cap edges and over the tubing, allowing the camera to image most of the cap area. The region covered by the tubes, however, remained obstructed from view.

TEST APPARATUS

A digital thermography system was used to inspect most of the caps during bonding and all of the caps after the bonding process was complete and the vacuum bagging materials removed. An Amber Radiance 1T infrared camera, with a 13 mm lens and a 12" x 12" field of view, was used to image the caps after flash heating. A Thermal Wave Imaging EchoTherm data acquisition system was used to record the digital images from the camera to files on a PC hard drive. A Thermal Wave Imaging flash hood set to deliver 6.4 kJ of energy was used to rapidly heat the caps prior to image acquisition.

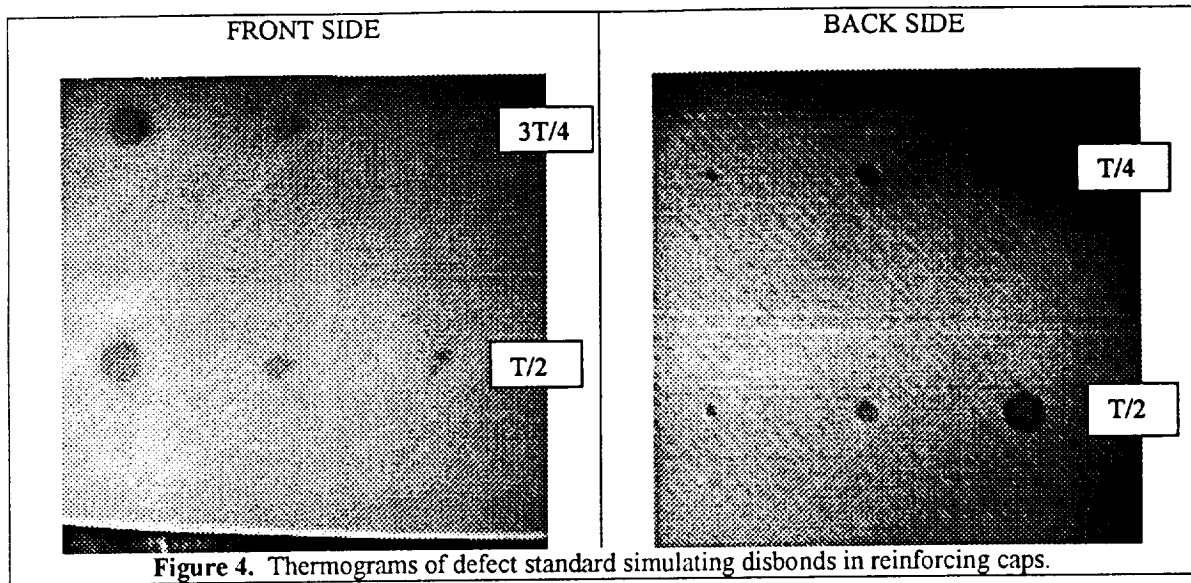
An analog thermography system was also used for some of the cap inspections. The analog system, although lower in sensitivity than the digital system gave real-time images of the uncured bond line and as such gave the fabrication team more time to work out any trapped air. Here, an Inframetrics SC-1000 infrared camera was used to image the caps after slow heating by way of a pair of 500W hand-held quartz shop lamps. Thermal images from the camera were recorded to VHS tape.

DEFECT STANDARDS

Reinforcing Cap Defects

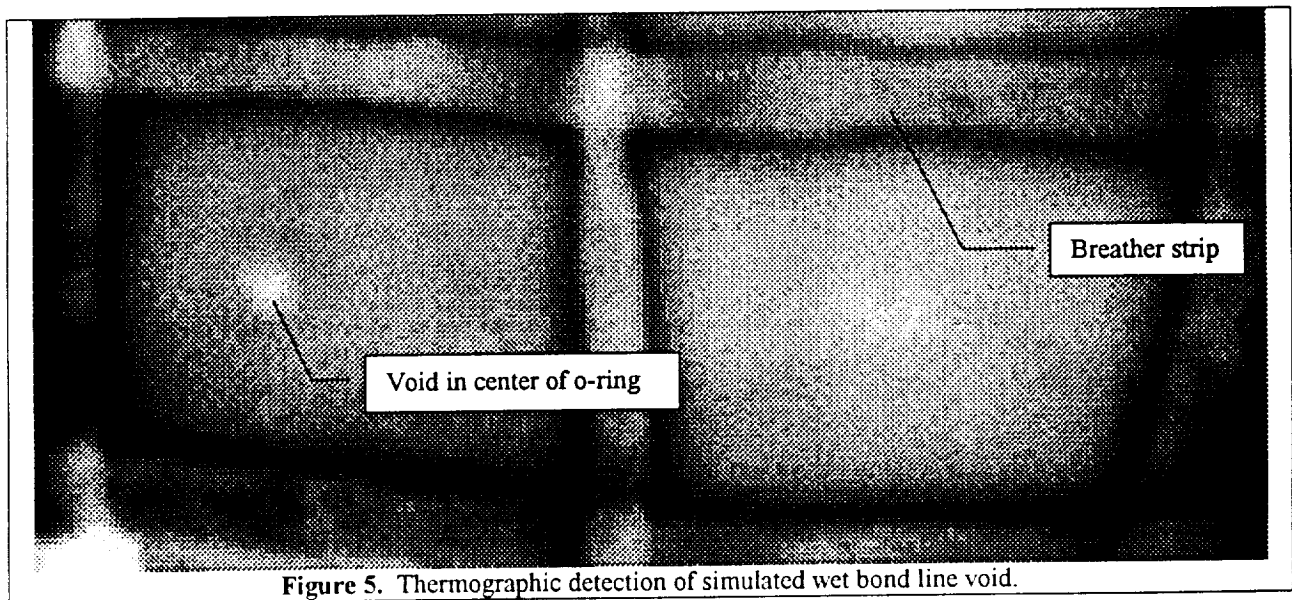
Inspection of the wet bond line may have also detected defects in the reinforcing caps above the bond line. Defect standards were fabricated to simulate defects in the reinforcing caps themselves. Inserts were fabricated into sample panels between plies at various depths to simulate internal unbonds. The images shown in Figure 4 were acquired

with the digital system previously described, with the exception that a 25 mm lens (6"x6") field of view was employed. In the images the depth of the insert is given as a fraction of the panel thickness (T). Three insert diameters were used including 0.50, 0.25 and 0.125 inch.



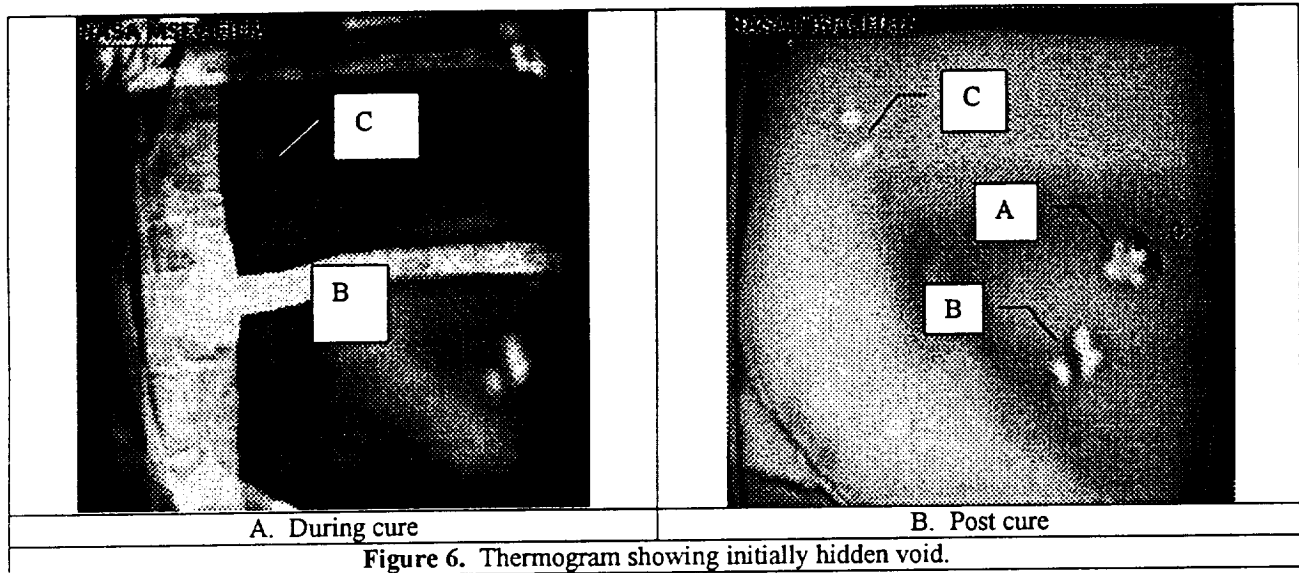
Bond line Defects

As a method to simulate unbonds during cure a defect panel was fabricated with inserts in the wet bond line. The simulated void shown thermographically in Figure 5 was produced by inserting a 0.5 inch diameter rubber o-ring between the simulated cap and underlying material. The cap was covered with a layer of release ply and vacuum bagged. Narrow strips of breather cloth were used in this instance rather than the split plastic breather tubes. The part was then inspected by heating the surface with a pair of shop lamps for about 10 seconds. Note how the void trapped within the o-ring remains hotter than the surrounding bond line demonstrating the presence of a void.



INSPECTION RESULTS

As previously described, the initial inspections were performed when the caps were still under the vacuum bag. In this manner, voids or air pockets, trapped under the cap could be eliminated before the cure was complete or if the void was less than a previously determined critical size it could be accepted. Figure 6 demonstrates a thermogram of a cap section with two small, but acceptable, voids. When the part was cured and the bag removed a second inspection was performed (Figure 6b) revealing the first two known defects (B and C) as well as one that was hidden (A) beneath the breather ply strip.



On average it took six image sequences to fully cover each cap. The results of thermography inspection of a reinforcing cap which did not reveal any unacceptable unbonds are shown in Figure 7. The images shown here were obtained after the bond line had cured and the vacuum bag had been removed. Minor temperature variations exist due to differences in the thickness of a foam filler material beneath the cap. A grid of hot points is visible where vent ports were drilled in the reinforcing cap to prevent the entrapment of air between the foam and the cap.

The results of thermography inspection of a reinforcing cap which revealed an unacceptable unbond are shown in Figure 8. Again, these images were obtained after the vacuum bag had been removed. A branching unbond is visible in the upper left sector with a maximum length of approximately 4.4 inches. The unbond was just barely visible in the thermograms taken before the vacuum bag was removed being all but totally obscured by breather tubes and cloth that was placed around the outer edge of the panel.

Since this defect was unacceptably large an action was taken to try to fill the void with epoxy. To aid in the repair process lead foil tape markers were placed on the cap identifying the exact location of each leg of the void and verified by re-inspecting the region. Holes were then drilled in the reinforcing cap over the void and injected with epoxy to fill it. Thermograms were taken at various stages in this process are shown in Figure 9. After the third injection of epoxy, the size of the void had been diminished sufficiently that it was deemed acceptable.

The same process of thermographically inspecting each cap during and after cure was performed for the rest of the tank. Defects found after the post cure inspections were measured and if deemed necessary filled with resin. A final post repair check was then performed to complete the inspection process.

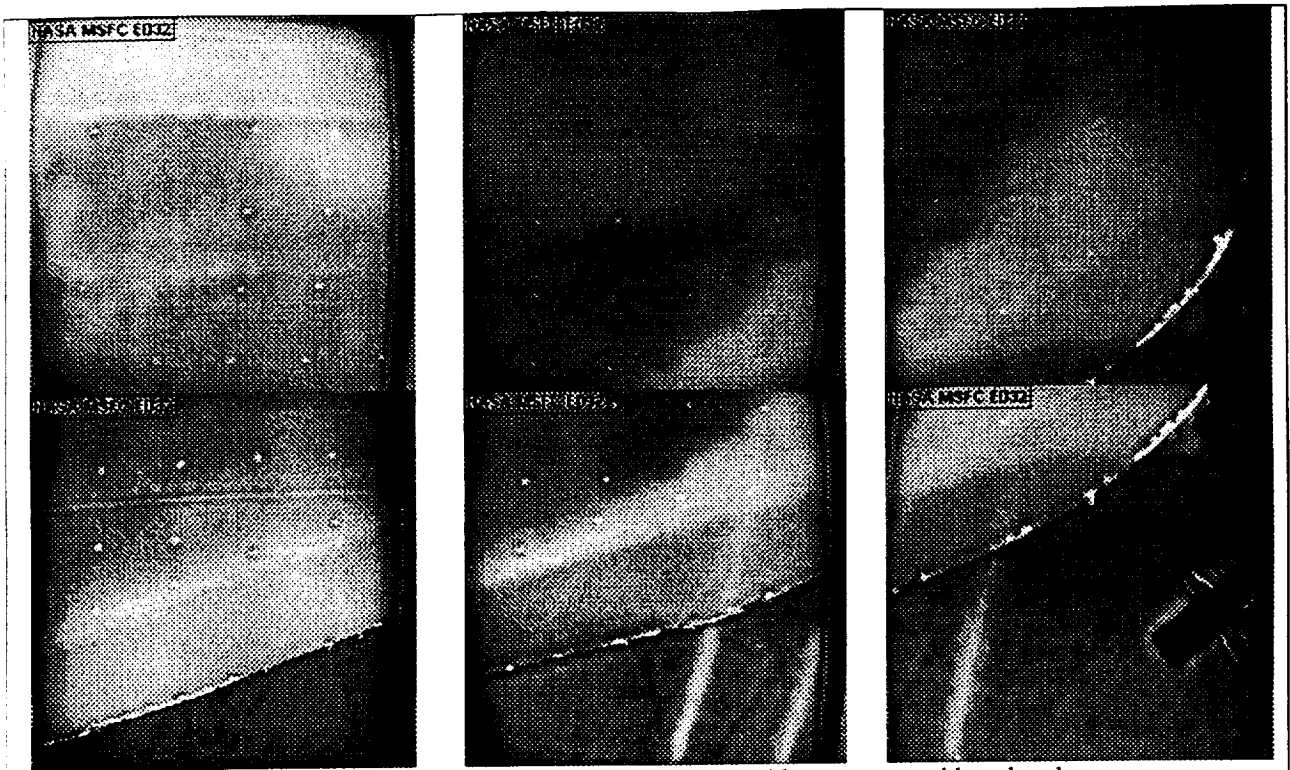


Figure 7. Sector inspections of a reinforcing cap with no unacceptable unbonds.

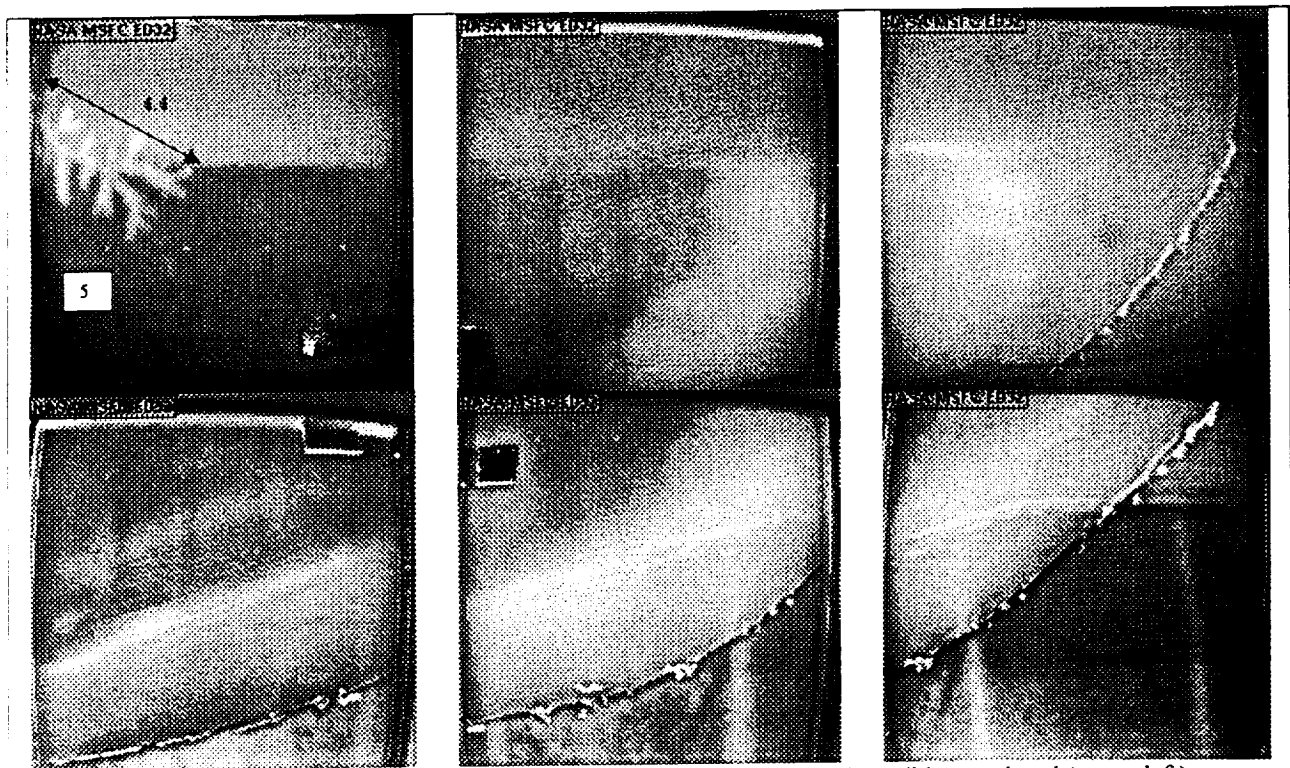


Figure 8. Sector inspections of a reinforcing cap with an unacceptable 4.4" long unbond (upper left).

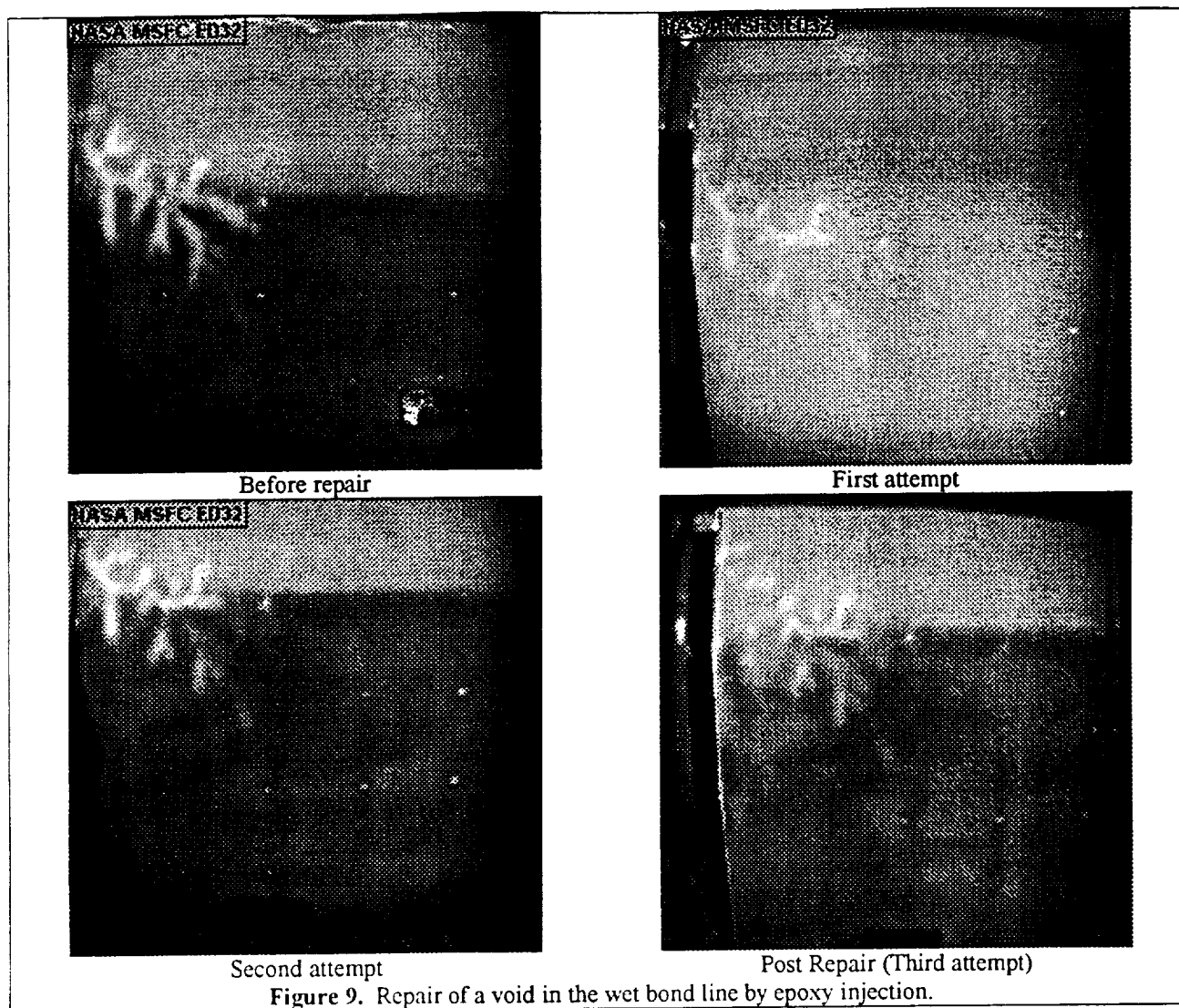


Figure 9. Repair of a void in the wet bond line by epoxy injection.

CONCLUSIONS

Thermographic inspection proved largely successful in the detection of voids in the wet bond line between reinforcing caps and underlying foam filler on the X-33 LH₂ Tank 2. Voids that were detected precure were often eliminated by rubbing them out or removing and reshaping the cap. There were some undetected voids that had either opened up after the initial thermographic inspection or were obscured by the breather tubes used in vacuum bagging. Epoxy was injected to fill these voids, resulting in an acceptable repair.

ACKNOWLEDGEMENTS

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